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Vapor compression multifunctional heat pumps in China: A review of configurations and operational modes

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ABSTRACT

With the growing concerns about worldwide energy and environmental sustainability, heat pump water heaters and solar water heaters became popular in China after 2000. The combinations between the heat pump air conditioner, heat pump water heater and solar water heater brought about more energy saving operational modes besides those included in the above three appliances, which promoted the development of multifunctional heat pumps. The combinations also resulted in the higher utilization ratio and lower operational cost of the heat pump, then the payback time can be shortened greatly. The rapid development of multifunctional heat pumps at the beginning of the 21st century in China indicates its promising application prospect.

The heat pump air conditioner was the fundamental component of a multifunctional heat pump. Versatile configurations of multifunctional heat pumps were evolved from the integration of the domestic water heat exchanger with the refrigerant loop of the heat pump air conditioner by various approaches. This paper reviewed the development of multifunctional heat pumps in China, mainly focusing on configuration features and operational modes of the heat pump. The configuration of a multifunctional heat pump fundamentally determines the initial cost, operating cost and operating reliability. Therefore, it is reasonable to make a compromise between the simplicity of the configuration and versatile operational modes in the design of the multifunctional heat pump under different application conditions.

Contents

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1. Introduction

A heat pump is a device that can "pump" heat from a heat source to a higher temperature heat sink, which is somewhat analogous to a water pump. The heat pump is able to produce heat by using only small fraction of the required energy as William Thomson (later became to be known as Lord Kelvin) claimed in 1852, which was called "heat multiplier" [1].

There are two general kinds of heat pumps: vapor compression heat pumps and vapor sorption heat pumps, which are driven by the mechanical work and high-temperature heat energy, respectively. The vapor compression heat pumps were mostly concerned and they were denoted by "heat pump" in this paper with no particular definition.

Air source heat pumps first proposed by Thomson use the ambient air as a heat source or sink, which have been most widely used due to their relatively easy and inexpensive installations. In 1855, Rittinger [2] built the first practical heat pump to dry salt in salt marshes in Austria. The first known record of the concept of using the ground as the heat source for a heat pump with a ground loop was in a Swiss Patent issued to Herinrich Zoelly in 1912 [3]. However, the large temperature difference during periods of extreme cold or hot weather will lead to efficiency decline, which limited the application of heat pumps.

Since Haldane [4] demonstrated in his detailed experiments that heat pump can be made to operate in either the heating mode or the cooling mode in 1927, the use of heat pumps has been highly successful in people's homes from 1940s to 1950s, especially in those regions where both heating and cooling are required, because the cost of a heat pump system can be spread over both heating and cooling seasons. But in 1960s, the electricity price was on the decline, the application of heat pumps was limited by their high initial costs and poor reliabilities compared with the electrical heaters.

From the beginning of the 1970s, the heat pump was again found favor with people due to the oil crisis. Research was conducted to develop new technologies on the performance improvement of the heat pump in many countries. Alternative energy sources were also taken into consideration for heat pump energy production, such as solar energy, geothermal energy, etc. Hybrid energy source heat pumps began to be developed and the employment of energy sources for the heat pump in several ways were proposed by many researchers [5]. Especially, the employment of solar energy was received considerable attentions [6–10].

In a solar assisted heat pump, solar energy is supplied to the evaporator for raising its temperature and then improving the system performance, while in a solar-driven heat pump the solar energy functions as the driven energy. The solar assisted heat pump can be further divided into two types: the conventional solar assisted heat pump (SAHP) or the indirect-expansion solar assisted heat pump (IX-SAHP), and the direct-expansion solar assisted heat pump (DX-SAHP) [6,7].

IX-SAHP was proposed in 1950s [8], in which the solar collector and outdoor heat exchanger (also called ambient heat exchanger) were separate units and water was usually used as the collector fluid. DX-SAHP was proposed after IX-SAHP [9], in which the solar collector and outdoor heat exchanger were combined into one unit. The refrigerant from the condenser was expanded and boiled directly in the solar collector/evaporator, which can improve the thermal performance due to the elevated evaporating temperature from the direct solar energy input.

The early solar assisted heat pumps were usually classified as parallel, series and dual-source systems according to the source of heat supplied to the evaporator [10]. In the series system, only solar energy was supplied to the outdoor heat exchanger, thus the IX-SAHP can provide the solar assisted space heating and solar water heating operational modes. In the parallel system, the refrigerant loop and solar collector fluid loop were connected in parallel with the indoor heat exchanger (also called service heat exchanger), thus the collected solar energy was supplied directly for the space heating and the heat pump received energy only from the atmosphere. The dual-source system was a hybrid of the series and parallel systems.

The development of heat pumps in China was relatively late compared with the developed countries [11]. The earliest research was started in Tianjin University in the 1950s but the industrial application of heat pump began at the beginning of the 1960s. The first window-type heat pump air conditioner was developed by Shanghai Refrigerator Factory in 1965, but its application was blocked due to the poor reliability of the four-way valve. In the same year, the first water source heat pump was developed by Tianjin Refrigerating Machine Works and Tianjin University.

In the 1970s and 1980s, the advanced production lines of heat pump air conditioners began to be brought in from abroad. Split-type air conditioners were developed. The applications of air source industrial and residential heat pumps increased as well as water source and ground source heat pumps.

Late in 1980s, considerable attentions have been given to the autonomic research and development of heat pumps [12,13]. In the 1990s, the production of heat pumps increased dramatically and heat pump air conditioners became widespread in China as well as the water source heat pump air conditioning systems. China also became one of the biggest producers of heat pump air conditioners. Most of the research focused on the improvement of the heat pump configuration and performance.

Impacted from the worldwide energy shortage, the ground source heat pump [14,15], solar assisted heat pump and solar-ground heat pump [16,17] also began to be developed in the 1990s. The functional modes of heat pumps also began to change from the common space cooling and space heating, for example, heat pumps can possess the common space cooling and heat pump water heating functional modes together [12,15].

In the 21st century, the heat pump air conditioner and water heater gradually became the necessities for residences and workplaces as the living standard improved in China. The heat pump water heater was developed rapidly due to its safety and electricity saving merits compared with the gas water heater and the electric water heater, but its high initial cost and low utilization ratio limited its applications as well as the solar water heater.

The heat pump air conditioner, heat pump water heater and solar water heater cannot provide the three necessary functions

Table 1
The outline of the different types of the introduced multifunctional heat pumps.

Categories	Types					
Two-heat-exchanger systems	(A) A four-way valve employed systems			(B) No four-way valve employed systems		
Three-heat-exchanger systems	(A) A third heat exchanger integrated between the compressor and four-way valve		(B) A third heat exchanger integrated after the four-way valve		(C) A third heat exchanger integrated in parallel with the four-way valve	
	(A1) Connected in serial	(A2) Connected in parallel	(B1) Connected in serial	(B2) Connected in parallel	(C1) Connected with a two-way (three-way) valve	(C2) Connected with a four-way valve
Multi-heat-exchanger systems	(A) High temperature water systems	(B) Thermal storage systems		(C) Supplementary heat source systems	(D) Recuperating systems	

of modern life separately: space cooling, space heating and domestic water heating. Therefore, the combination between the heat pump air conditioner and heat pump water heater or the solar water heater was inevitable, which led to the multifunctional heat pump came into being. The multifunctional heat pump can be defined as a heat pump with the above three necessary functions of modern life. The rapid development of multifunctional heat pumps at the beginning of the 21st century in China indicates its promising application prospect.

The combination of the heat pump air conditioner and heat pump water heater [18] appeared earlier than that of the heat pump air conditioner and solar water heater [19], which are the two major development approaches of the multifunctional heat pumps. These combinations brought about more energy saving operational modes besides the modes included in the above three appliances, which resulted in the higher utilization ratio of the heat pump and lower operational cost, therefore, the payback time can be shortened greatly.

The heat pump air conditioner is the fundamental part of the multifunctional heat pump because it embodies two of the three necessary functions. Namely, the compressor, indoor heat exchanger, outdoor heat exchanger and expansion valve which are the four necessary components in the refrigerant loop of a heat pump air conditioner should be included in a multifunctional heat pump, and moreover, a hot water heat exchanger is also necessary for domestic water heating. Therefore, the integrating means of the hot water heat exchanger in the refrigerant loop will mainly determine the configuration of a multifunctional heat pump. According to the amount of heat exchangers in the refrigerant loop, multifunctional heat pumps can be classified in the following three categories: (1) two-heat-exchanger systems; (2) three-heat-exchanger systems; (3) multi-heat-exchanger systems.

In the following chapters, the paper will introduce the development of the multifunctional heat pumps in China which are outlined in Table 1, and mainly focused on configuration features and operational modes of these heat pumps.

2. Two-heat-exchanger systems

In the two-heat-exchanger system, the domestic water heat exchanger was directly integrated into the outdoor or indoor heat exchanger. According to the employment of the four-way valve in the refrigerant loop, the two-heat-exchanger system can be further divided into the following two types: (A) a four-way valve employed; (B) no four-way valve employed.

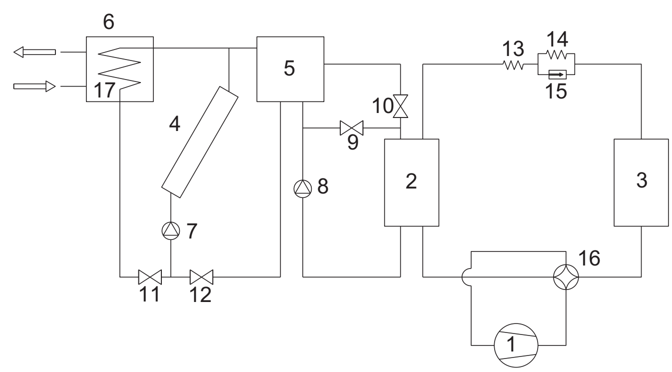

Fig. 1. Flow chart of a two-heat-exchanger system in which the domestic water heat exchanger was combined with the outdoor heat exchanger: (1) compressor; (2) outdoor compound heat exchanger; (3) indoor heat exchanger; (4) solar collector; (5) domestic water tank; (6) auxiliary water tank; (7, 8) water pumps; (9, 12) water valves; (13, 14) expansion valves; (15) check valve; (16) four-way valve; (17) auxiliary water heat exchanger [20].

2.1. A four-way valve employed

In 2007, Zhou et al. [20] proposed a two-heat-exchanger system evolved from the series system of IX-SAHP, in which a four-way valve was employed and a tube-in-tube compound heat exchanger combined the domestic water heat exchanger and outdoor heat exchanger into one unit (Fig. 1). The inner and outer tubes of the compound heat exchanger were the water and refrigerant channels, respectively. In the air side of the compound heat exchanger, there were fins outside the outer tubes.

The system provided five operational modes: common space cooling, common space heating, space cooling/heat pump water heating, solar assisted space heating and solar water heating. In the space cooling/heat pump water heating mode. The system can operate for space cooling and heat pump water heating simultaneously.

Though the system can produce enough domestic water in the space cooling season by the solar water heating or heat pump water heating, the domestic water can only produced by the solar water heating mode in the space heating season, because the compound heat exchanger cannot function as a condenser in the common space heating or solar assisted space heating modes. Therefore, the domestic water production depended heavily on the weather in the space heating season.

Zhou et al. [21] also proposed a similar solar assisted two-heat-exchanger system, but the ground source was supplied to the heat pump instead of air source, in which the compound heat exchanger was transformed as three channel type for exchanging heat between the refrigerant, domestic water and geothermal

fluid. The system provided the same operational modes with the similar special compound heat exchanger, which simplified the configuration of the heat pumps but increased difficulties in manufacture.

In 2005, Sun et al. [22] described a two-heat-exchanger system from the parallel system of IX-SAHP, in which a four-way valve was employed and a common water-refrigerant heat exchanger combined the domestic water heat exchanger and the indoor heat exchanger into one unit (Fig. 2). The system provided five operational modes: common space cooling, common space heating, heat pump water heating, solar water heating and solar space heating.

Though the system can produce enough domestic water in the space heating season by the solar water heating or heat pump water heating mode, the domestic water can also only produced by the solar water heating mode in the space cooling season, because the indoor heat exchanger cannot function as a condenser in the common space cooling mode. Therefore, the domestic water production depended heavily on the weather in the space cooling season.

Yuan [23] presented a similar solar assisted two-heat-exchanger system which provided the same operational modes. In the system a gas fired boiler was employed for water heating in case of insufficient sunshine, but the resulting additional heat source loop add intricacy to the system configuration.

In 2007, Luo [24] designed a two-heat-exchanger system, in which a four-way valve was employed and the domestic water tank heat exchanger was integrated into the outdoor and indoor heat exchangers together (Fig. 3). Similar to Ref. [20], a special compound heat exchanger was also used in place of the outdoor heat exchanger. Moreover, it can absorb solar energy from its air side surface to produce domestic water. Therefore, the system provided two additional operational modes: heat pump water heating and solar assisted water heating. In the solar assisted water heating mode, the solar energy was used as heat source for the heat pump water heating to increase the evaporating temperature and then improve heat pump performance in low ambient temperature seasons.

But this system also cannot ensure the domestic water supply when the sunshine was insufficient in the space cooling season because the heat pump water heating mode cannot be operated due to the indoor heat exchanger functioning as the evaporator. Problems in manufacture of the special outdoor compound heat exchanger were also remained.

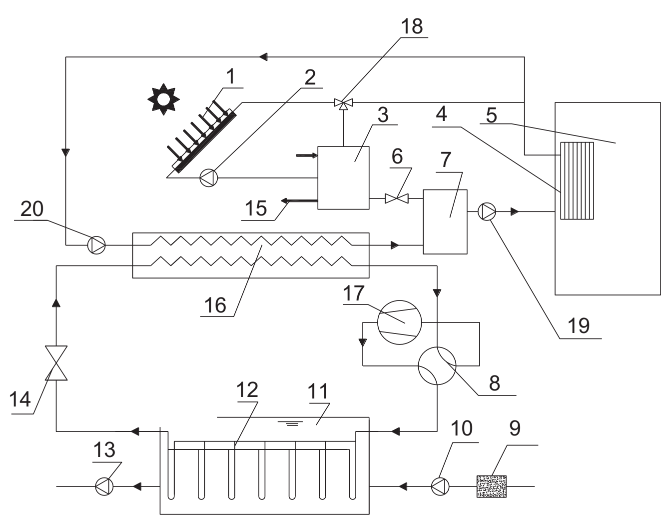

Fig. 2. Schematic diagram of a two-heat-exchanger system in which the domestic water heat exchanger was combined with the indoor heat exchanger: (1) solar collector; (2, 19, 20) water pumps; (3) auxiliary water tank; (4) fan coil; (5) air-conditioning room; (6) domestic water tank; (7) valve; (8) four-way valve; (9) filter; (10, 13) water pumps; (11) reservoir; (12) outdoor heat exchanger; (14) expansion valve; (15) auxiliary water outlet; (16) indoor heat exchanger; (17) compressor; (18) three-way valve [22].

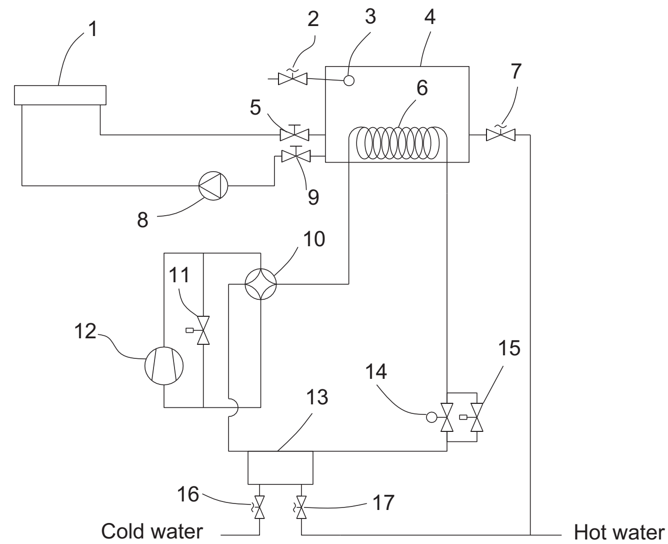

Fig. 3. Schematic view of a two-heat-exchanger system in which the domestic water tank heat exchanger was integrated into the indoor and outdoor heat exchangers together: (1) fan coil; (2, 7, 16, 17) water valves; (4) domestic water tank; (5, 9) control valves; (6) indoor heat exchanger; (8) water pump; (10) four-way valve; (11, 15) bypass valves; (12) compressor; (13) outdoor compound heat exchanger; (14) expansion valve [24].

2.2. No four-way valve employed

In 2009, He et al. [26] introduced a two-heat-exchanger system, in which no four-way valve was employed and the domestic water heat exchanger was integrated into the outdoor heat exchanger with a special heat pipe type compound heat exchanger and an auxiliary water heat exchanger was integrated into the indoor heat exchanger (Fig. 4). The domestic water tank and auxiliary water tank were connected in parallel with the fan-coil in the water loop. The system provided not only the seven operational modes included in the system of Ref. [24], but also the solar space heating mode. Of course, the water loops became very complicated.

2.3. Summary

In order to provide the three necessary functions: space cooling, space heating and domestic water heating, one of the outdoor and indoor heat exchangers should be at least combined with the domestic water heat exchanger in the above two-heat-exchanger systems [20–26], which brings two limitations. If the outdoor heat exchanger is combined with the domestic water heat exchanger, a special compound heat exchanger should be employed to absorb the air heat for the common space heating mode and an additional heat source should be employed for water heating in winter time. If the indoor heat exchanger is combined with the domestic water heat exchanger, an auxiliary domestic water tank and an additional heat source should be employed for water heating in the space cooling season.

Refrigerant loops of these two-heat-exchanger systems are similar to those of the heat pump air conditioners, simple and reliable. But the second refrigerant loops, i.e. the domestic water loop and solar collector fluid loop became complex in order to operate the various modes, which is more obvious for the systems

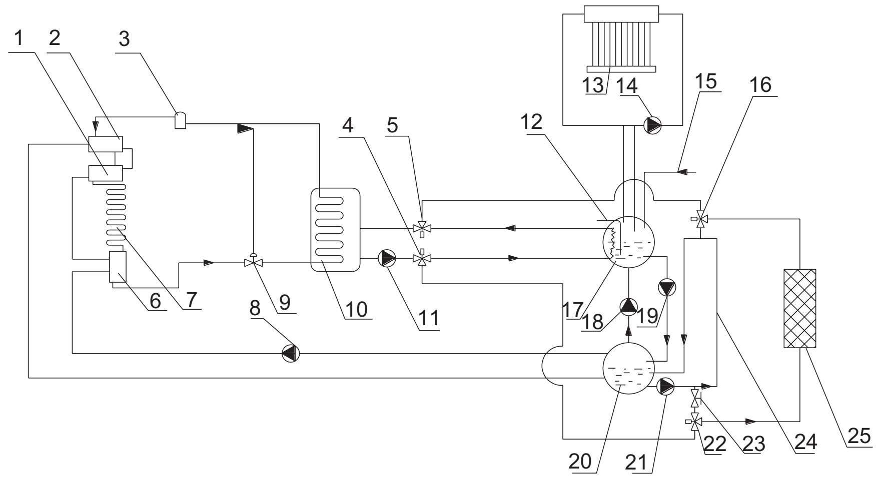

Fig. 4. Sketch of a two-heat-exchanger system in which the domestic water and auxiliary water heat exchangers were combined with the indoor and outdoor heat exchangers respectively: (1, 2, 6) heat pipe heat exchangers; (3) compressor; (4, 5, 16, 22) three-way solenoid valves; (7) outdoor heat exchanger; (8, 11, 14, 18–21) water pumps; (9) expansion valve; (10) indoor heat exchanger; (12) electric heater; (13) solar collector; (17) auxiliary water tank; (20) domestic water tank; (23) two-way solenoid valve; (25) fan coil [26].

without a four-way valve. Therefore, two-heat-exchanger systems are more suitable for large-size applications considering the potential manufacture difficulties inherent in the special compound heat exchanger and potential control problems inherent in switching of the operational modes with complicated second refrigerant loops.

3. Three-heat-exchanger systems

Because the air-cooled indoor and outdoor heat exchangers were very popular in many heat pump applications, additional domestic water heat exchanger was necessary in the refrigerant loop for such applications to provide the three necessary functions of the multifunctional heat pump. According to the location of the domestic water heat exchanger in the refrigerant loop, the three-heat-exchanger systems can be further divided into the following three types: (A) between the compressor and four-way valve; (B) after the four-way valve; (C) in parallel with the four-way valve.

3.1. The domestic water heat exchanger integrated between the compressor and four-way valve (A)

In this type of three-heat-exchanger systems, the domestic water heat exchanger was integrated into the high pressure refrigerant lines between the compressor and four-way valve. The integration can be further divided into the following two types: (A1) connection in serial; (A2) connection in parallel.

3.1.1. Connection in serial with the high pressure refrigerant lines (A1)

Peng [27] proposed a three-heat-exchanger system of type A1 with two bypass lines for the indoor and outdoor heat exchangers in 2005, in which the domestic water heat exchanger was connected in serial with high pressure refrigerant lines between the compressor and four-way valve, and can only function as a condenser for heat pump water heating (Fig. 5). The system provided four operational modes: common space cooling, common space heating, heat pump water heating and space cooling/heat pump water heating.

The employment of bypass lines for indoor and outdoor heat exchangers can eliminate the unnecessary pressure losses in these heat exchangers when the heat pump operated in the heat pump water heating and space cooling/heat pump water heating modes, which is helpful to improve the thermal performance. But it resulted in potential serious control problems because the solenoid pilot actuated valves cannot ensure the two-direction refrigerant flow controls in bypass lines.

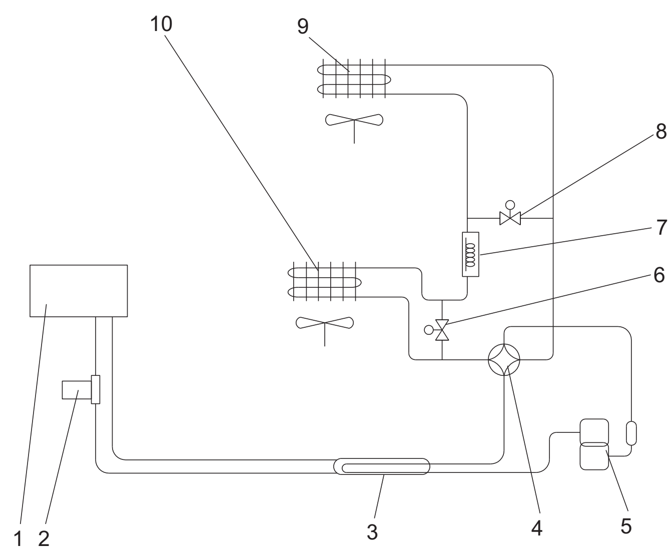

Fig. 5. Flow sheet of a three-heat-exchanger system of type A1 with bypass lines for the indoor and outdoor heat exchangers: (1) domestic water tank; (2) water pump; (3) domestic water heat exchanger; (4) four-way valve; (5) compressor; (6, 8) solenoid valves; (7) expansion valve; (9) indoor heat exchanger; (10) outdoor heat exchanger [27].

The earliest similar system did not employ the bypass lines [18] and some other similar systems only employed one bypass line for the indoor heat exchanger [28–30], but they provided the same four operational modes as the system in Ref. [27].

In 2008, Mu [31] presented a three-heat-exchanger system of type A1 with a refrigerant rectification module consisted of a receiver, an expansion valve, a filter–dryer and four check valves, in which the refrigerant can flow through the receiver and expansion valve in the same direction and the necessary refrigerant masses can be effectively regulated in different operational modes (Fig. 6).

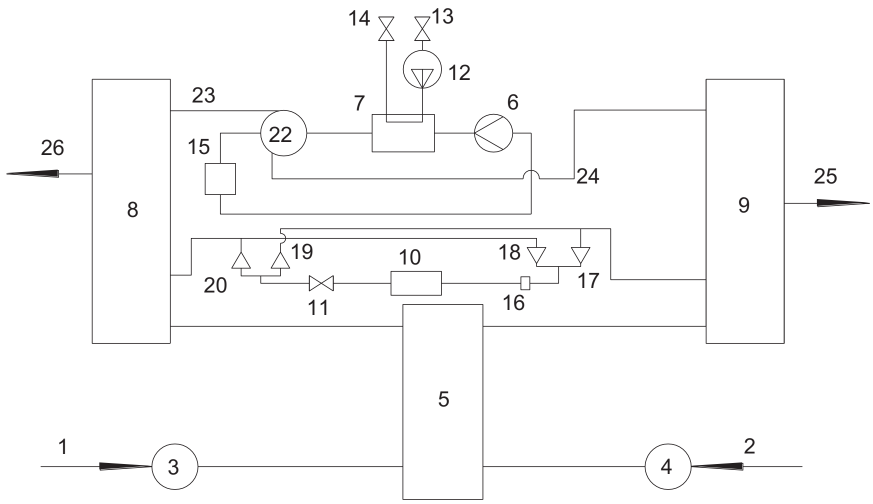

Fig. 6. Cycle layout of a three-heat-exchanger system of type A1 with a refrigerant rectification module: (5) heat recovery heat exchanger; (6) compressor; (7) domestic water heat exchanger; (8) outdoor heat exchanger; (9) indoor heat exchanger; (10) filter–dryer; (11) expansion valve; (12) water pump; (15) gas–liquid separator; (16) receiver; (17–20) check valves; (21) domestic water tank; (22) four-way valve [31].

3.1.2. *Connection in parallel with the high pressure refrigerant lines (A2)*

In 2006, Li [32] designed a three-heat-exchanger system of type A2 with a bypass line for the indoor and outdoor heat exchangers, in which the domestic water heat exchanger was connected in parallel with high pressure refrigerant lines between the compressor and four-way valve (Fig. 7). The domestic water heat exchanger can also function only as a condenser for heat pump water heating, and its start–stop was controlled by a two-way valve.

The bypass line in this system was connected in parallel with the four-way valve, which was different from the way in the system of Ref. [27] but for the same purpose and effect, i.e., the unnecessary pressure losses can be eliminated in the indoor and outdoor heat exchangers when the heat pump operated in the heat pump water heating and space cooling/heat pump water heating modes. It resulted in superior reliable control performance of the system in the same four operational modes due to the reliable one way refrigerant flow control from the solenoid valve and check valve on the bypass line, when compared with the bypass line design in Ref. [27].

The earliest three-heat-exchanger system of type A2 did not employ the bypass line [33], while the bypass line designs in some other systems of type A2 [34,35] were similar to the design in Ref. [27].

In 2009, Ye [36] also introduced an interesting three-heat-exchanger system of type A2 with three four-way valves, in which the second four-way valve replaced the solenoid valve 81 in the system of Ref. [32] and a third four-way valve replaced the two solenoid valves in the system of Ref. [27] (Fig. 8). The new bypass line designs ensured reliable operations of the same four modes as Ref. [32].

In 2009, Wang et al. [37] proposed a three-heat-exchanger system of type A2 with a refrigerant rectification module consisted of a receiver, two expansion valves, and two check valves (Fig. 9), in which a solar collector was integrated into the domestic water heat exchanger, indoor and outdoor heat exchangers with the domestic water and collector fluid loops respectively. Therefore, this system provided additional three operational modes of solar assisted water heating, solar assisted space heating and solar water heating compared with the above type A2 system.

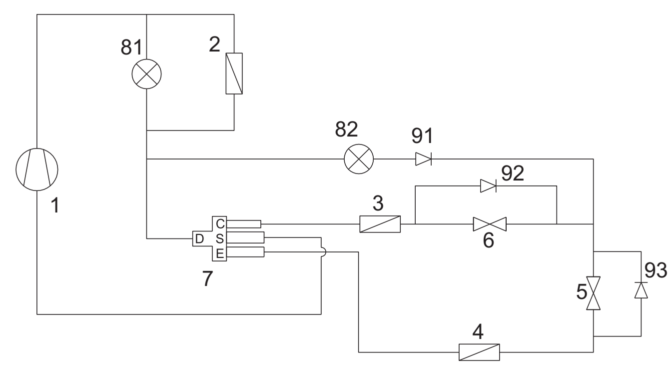

Fig. 7. Schematic view of a three-heat-exchanger system of type A2 with a different bypass line for indoor and outdoor heat exchangers: (1) compressor; (2) domestic water heat exchanger; (3) outdoor heat exchanger; (4) indoor heat exchanger; (5, 6) expansion valves; (7) four-way valve; (81, 82) solenoid valves; (91–93) check valves [32].

Besides the utilization of solar energy in the above three modes, the solar energy can also be used for regeneration of the non-freezing solution, which will ensure the reliable operation of the system in severe winter conditions.

From the above discussions on Refs. [27–37], it can be found that the operational modes in the type A1 and A2 systems are the same, but the type A2 system possesses the potential superior thermal performance due to the elimination of the unnecessary pressure loss in the serial connected domestic water heat exchanger of the type A1 system in the common space cooling mode or common space heating mode.

Though the integration of the domestic water heat exchanger between the compressor and four-way valve of the refrigerant loop is a simple and practical way, the domestic water heat exchanger cannot function as an evaporator because it is always connected in the high pressure line of the refrigerant loop.

3.2. *The domestic water heat exchanger integrated after the four-way valve (B)*

In this type of the three-heat-exchanger system, the domestic water heat exchanger was integrated into the refrigerant lines after four-way valve. The integration of the domestic water heat

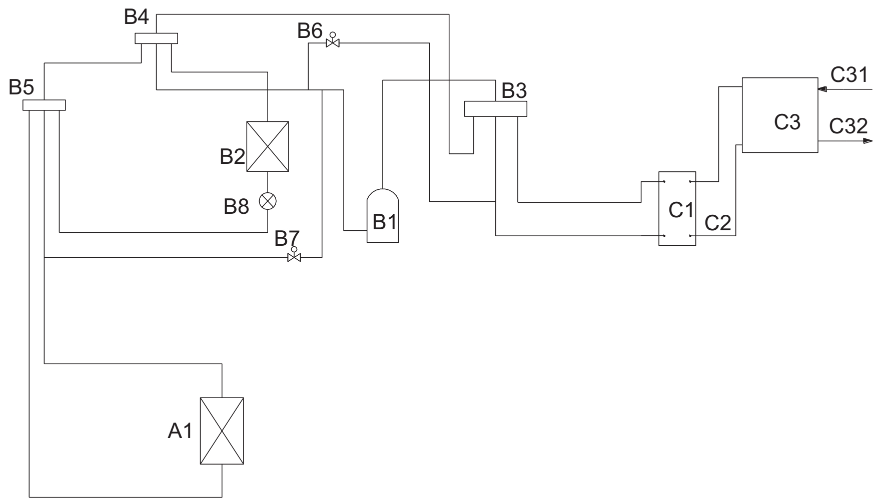

Fig. 8. Schematic diagram of a three-heat-exchanger system of type A2 with three four-way valves: (A1) indoor heat exchanger; (B1) compressor; (B2) outdoor heat exchanger; (B3) second four-way valve; (B4) original four-way valve; (B5) third four-way valve; (B6, B7) solenoid valves; (B8) expansion valve; (C1) domestic water heat exchanger; (C2) water pump; (C3) domestic water tank [36].

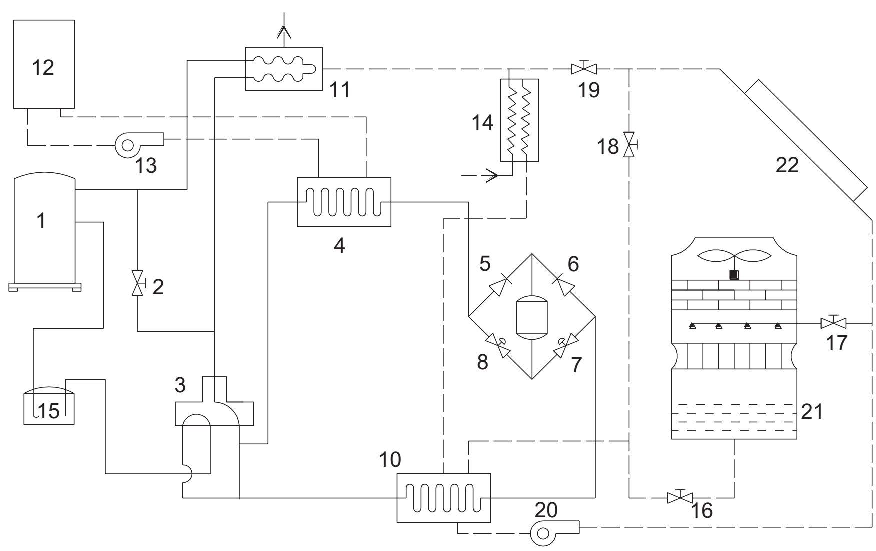

Fig. 9. Schematic drawing of a solar assisted three-heat-exchanger system of type A2 with a refrigerant rectification module: (1) compressor; (2,16–19) solenoid valves; (3) four-way valve; (4) LLL indoor heat exchanger; (5, 6) check valves; (7, 8) expansion valves; (9) receiver; (10) outdoor heat exchanger; (11) domestic water tank; (12) fan coil; (13) water pump; (14) collector fluid-water heat exchanger; (15) gas–liquid separator; (20) collector fluid pump; (21) cooling tower; (22) solar collector [37].

exchanger with the indoor and outdoor heat exchangers can be further divided into the following two types: (B1) connection in serial; (B2) connection in parallel.

3.2.1. *Connection in serial with the indoor and outdoor heat exchangers (B1)*

In 2006, Ding [38] described a three-heat-exchanger system of type B1 with a domestic water heat exchanger connected in serial between the four-way valve and outdoor heat exchanger, in which a solar collecting loop was integrated (Fig. 10). The domestic water heat exchanger can function as a condenser for the space cooling/heat pump water heating mode in the space cooling season and can also function as an evaporator for the hot water defrosting mode in the space heating season. In the hot water defrosting mode, the heat energy stored in the domestic hot water can be supplied for the fast defrosting to save electricity in the space heating season.

Thus the system can provide six operational modes: common space cooling, common space heating, space cooling/heat pump water heating, hot water defrosting and solar assisted space heating, solar water heating. Because there was no expansion valve between the domestic water heat exchanger and outdoor heat exchanger, the system cannot operate in the heat pump water heating mode. Hence the air source was unavailable for the water heating, and then domestic water supply depended heavily on the weather.

The early similar three-heat-exchanger system of type B1 did not employ the solar collecting loop [39], therefore, the solar assisted space heating and solar water heating modes were not included in the above six operational modes.

In 2006, Wang et al. [40] presented a three-heat-exchanger system of type B1 with a domestic water heat exchanger connected in serial between the indoor and outdoor heat exchangers, in which a solar collecting loop was also integrated but two expansion valves were employed (Fig. 11). Therefore, the heat

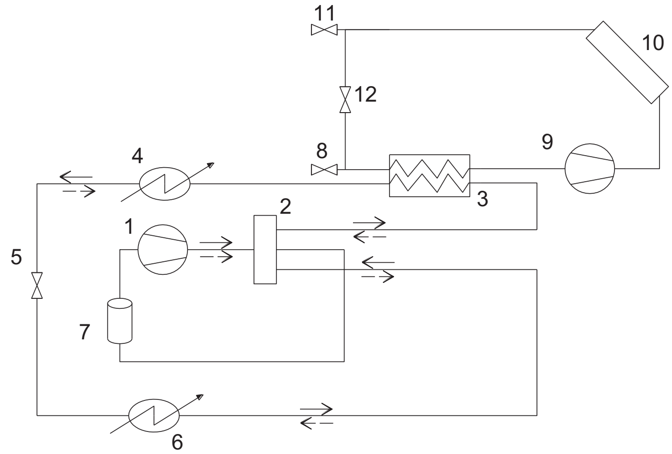

Fig. 10. Sketch of a three-heat-exchanger system of type B1 with a domestic water heat exchanger connected in serial between the four-way valve and outdoor heat exchanger: (1) compressor; (2) four-way valve; (3) domestic water heat exchanger; (4) outdoor heat exchanger; (5) expansion valve; (6) indoor heat exchanger; (7) gas–liquid separator; (8, 11) water valves; (9) water pump; (10) solar collector; (12) solenoid valve [38].

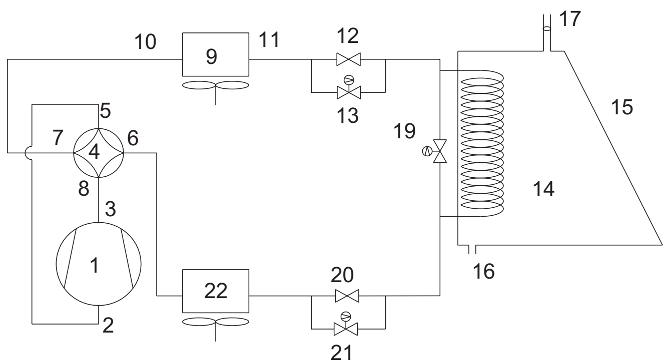

Fig. 11. Flow chart of a three-heat-exchanger system of type B1 with a domestic water heat exchanger connected in serial between the indoor and outdoor heat exchangers: (1) compressor; (4) four-way valve; (9) indoor heat exchanger; (12,20) expansion valves; (13,21) solenoid valves; (14) domestic water tank; (15) solar collector; (16) water inlet; (17) water export; (18) domestic water heat exchanger; (22) outdoor heat exchanger [40].

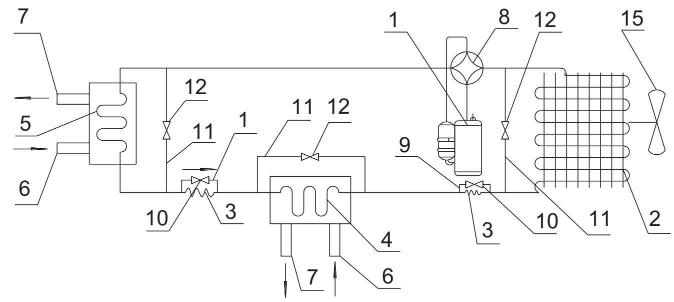

Fig. 12. Cycle layout of a three-heat-exchanger system of type B1 with a domestic water heat exchanger connected in serial between the four-way valve and indoor heat exchanger: (1) compressor; (2) outdoor heat exchanger; (3) expansion valve; (4) indoor heat exchanger; (5) domestic water heat exchanger; (6) water inlet; (7) water outlet; (8) four-way valve; (10–12) bypass valves; (15) fan [42].

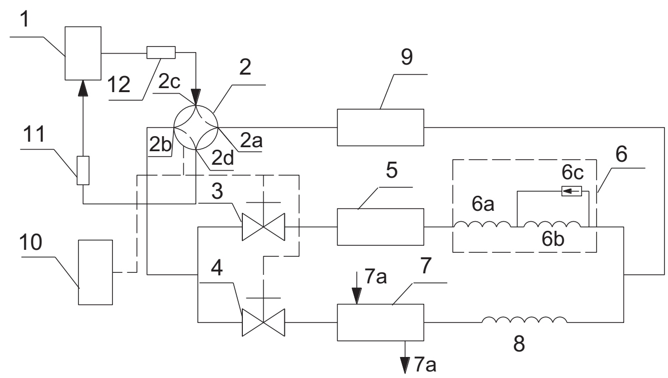

Fig. 13. Schematic drawing of a three-heat-exchanger system of type B2 with a domestic water heat exchanger connected in parallel with the indoor heat exchanger: (1) compressor; (2) four-way valve; (3, 4) solenoid valves; (5) indoor heat exchanger; (6a, 6b, 8) capillary tubes; (6c) check valve; (7) domestic water tank; (9) outdoor heat exchanger; (11) receiver; (12) filter [43].

pump water heating operational mode was operated besides the six modes included in the system of Ref. [38]. A bypass line for the domestic water heat exchanger was also employed, and then the unnecessary pressure loss in the domestic water heat exchanger can be eliminated when the heat pump only operated with the indoor and outdoor heat exchangers. But the thermal performance of the system still degraded in the operational modes with only one of the indoor and outdoor heat exchangers, because no bypass line was employed for either of the two heat exchangers.

The earliest three-heat-exchanger system of type B1 [41] was similar to the system in Ref. [40] but did not employ the solar collecting loop, therefore, the solar assisted space heating and solar water heating mode were not included.

In 2008, Zhu et al. [42] designed a three-heat-exchanger system of type B1 with a domestic water heat exchanger connected in serial between the four-way valve and indoor heat exchanger, in which two expansion valves were also employed but no solar collecting loop was integrated (Fig. 12). Three bypass lines were employed for three heat exchangers respectively, hence, each pair of the three heat exchangers can be coupled as a condenser and an evaporator or vice versa. If a solar collecting loop was integrated into the domestic water heat exchanger, the system provided the same operational modes as the system in Ref. [40].

From the above discussions on Refs. [38–42], it can be found that if two expansion valves and three bypass lines are employed as the system in Ref. [42], each pair of the three heat exchangers in the type B1 system can be coupled as the condenser and evaporator or vice versa, no matter where the domestic water heat exchanger is integrated after the four-way valve. Therefore, type B1 systems can provide all the operational modes as the system in Ref. [42].

Though the integration of the domestic water heat exchanger into the refrigerant loop after the four-way valve is also a simple and practical way, it almost cannot find a suitable location to place a refrigerant receiver which is very important for effective refrigerant managements in different operational modes. Therefore, it limits the applications of type B1 systems.

3.2.2. Connection in parallel with the indoor or outdoor heat exchanger (B2)

In 2004, Huang [43] proposed a three-heat-exchanger system of type B2 with a domestic water heat exchanger connected in parallel with the indoor heat exchanger after the four-way valve, in which no solar collecting loop was integrated (Fig. 13). Hence, the domestic water heat exchanger and indoor heat exchanger can function as a condenser separately or simultaneously as well as an evaporator, but they cannot be coupled as the condenser and evaporator to operate the space cooling/heat pump water heating mode. Thus the system can only provide four operational modes: common space cooling, common space heating, heat pump water heating and hot water defrosting.

In 2004, Chen [44] investigated a three-heat-exchanger system of type B2 with a domestic water heat exchanger connected in parallel with the outdoor heat exchanger after the four-way valve, in which a solar collecting loop was integrated and a refrigerant rectification module consisted of a receiver, two expansion valves, a sight glass, a filter–dryer and four check valves was employed (Fig. 14). Hence, the domestic water heat exchanger and outdoor heat exchanger can function as a condenser separately or simultaneously as well as an evaporator, but they cannot be coupled as the condenser and evaporator to operate the heat pump water heating mode. The system provided five operational modes: common space cooling, common space heating, space cooling/heat pump water heating, solar assisted space heating and solar water heating.

Similar systems were studied such as a geothermal-solar heat pump [45], systems integrated with a compound water tank [46] or an ejector [47].

In 2009, Wang et al. [48] presented a three-heat-exchanger system of type B2 with a domestic water heat exchanger connected in parallel with the indoor and outdoor heat exchangers together after the four-way valve, in which a solar collecting loop was integrated and a refrigerant rectification module consisted of a receiver, three expansion valves, two solenoid valves, a filter–dryer and three check valves was employed (Fig. 15).

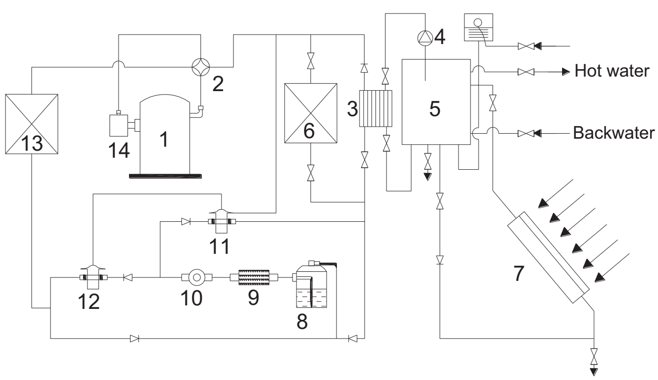

Fig. 14. Schematic diagram of a three-heat-exchanger system of type B2 with a domestic water heat exchanger connected in parallel with the outdoor heat exchanger: (1) compressor; (2) four-way valve; (3) domestic water heat exchanger; (4) water pump; (5) domestic water tank; (6) outdoor heat exchanger; (7) solar collector; (8) receiver; (9) filter–dryer; (10) sight glass; (11,12) expansion valves; (13) indoor heat exchanger; (14) oil separator [44].

Because each pair of the three heat exchangers can be coupled as a condenser and an evaporator or vice versa, the system can provide all of the seven operational modes included in the systems of Refs. [43,44].

The system was evolved from two primary systems [49,50] with few expansion valves but more solenoid valves and check valves. Other early similar systems usually did not employ the refrigerant rectification module [51,52].

From the above discussions on Refs. [43–52], it can be found that the refrigerant rectification module can be easily employed in the type B2 system for the refrigerant management in various operational modes. Compared with the type B1 system, the type B2 system possesses the potential superior operational reliability resulting in a better thermal performance.

Besides, researchers realized that the ordinary solenoid pilot actuated valves cannot ensure the two-direction refrigerant flow control, but tailored direct action solenoid valves are expensive. Therefore, it remained as a key problem which confines the application of type B2 systems.

3.3. *The domestic water heat exchanger integrated in parallel with the four-way valve (C)*

In this type of three-heat-exchanger system, the domestic water heat exchanger was integrated into the refrigerant lines in parallel with the original four-way valve. These systems can be further divided into the following two types according to the connecting valve: (C1) connection with a two-way or three-way valve; (C2) connection with a four-way valve.

3.3.1. *Connection with a two-way or three-way valve (C1)*

In 2005, Liu [53] proposed a three-heat-exchanger system of type C1 with a domestic water heat exchanger connected in parallel with the original four-way valve, in which one end of the heat exchanger was connected with the junction line between the compressor and four-way valve with a two-way valve, and the other end was connected with the junction line between indoor and outdoor heat exchangers (Fig. 16).

Because the domestic water heat exchanger was placed in the high pressure line of the refrigerant loop, it can only function as a condenser. Therefore, the system can provide four operational modes: common space cooling, common space heating, heat pump water heating and space cooling/heat pump water heating.

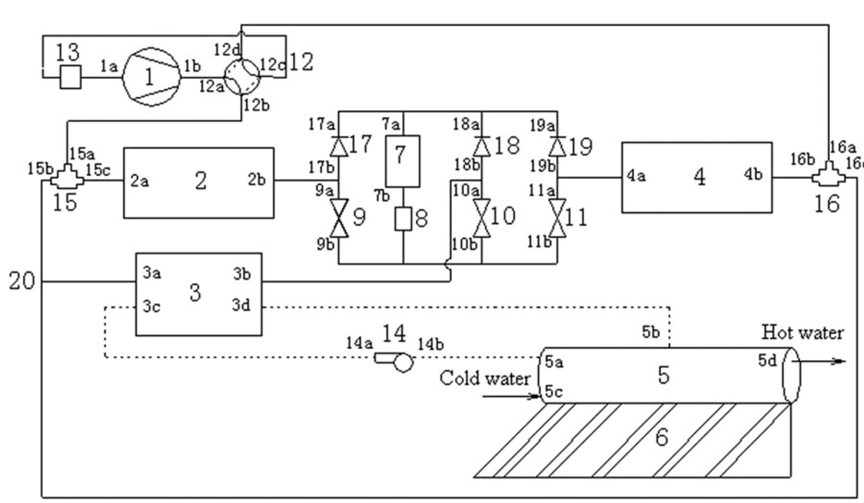

Fig. 15. Flow sheet of a three-heat-exchanger system of type B2 with a domestic water heat exchanger connected in parallel with the indoor and outdoor heat exchangers: (1) compressor; (2) indoor heat exchanger; (3) domestic water heat exchanger; (4) outdoor heat exchanger; (5) domestic water tank; (6) solar collector; (7) receiver; (8) filter–dryer; (9–11) expansion valves; (12) four-way valve; (13) gas–liquid separator; (14) water pump; (15,16) three-way valves; (17–19) check valves [48].

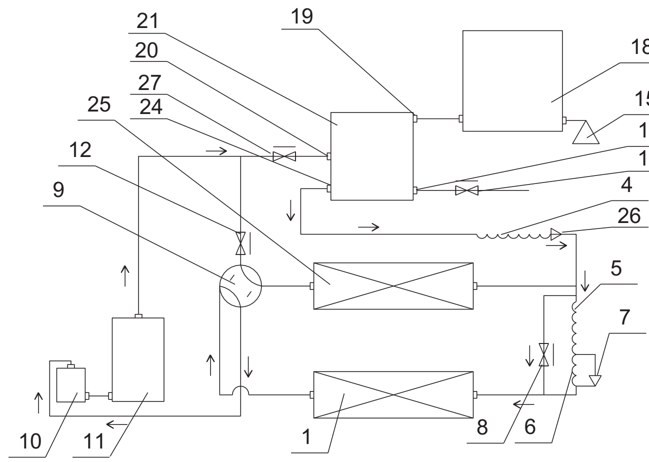

Fig. 16. Sketch of a three-heat-exchanger system of type C1 in which a domestic water heat exchanger was connected with a two-way valve and no receiver was employed: (1) indoor heat exchanger; (4–6) capillary tubes; (7, 26) check valve; (8, 12, 27) solenoid valves; (9) four-way valve; (10) gas–liquid separator; (11) compressor; (14) outdoor heat exchanger; (15) shower; (16) solenoid water valves; (17) water inlet; (18) domestic water tank; (19) water outlet; (21) domestic water heat exchanger; (25) outdoor heat exchanger [53].

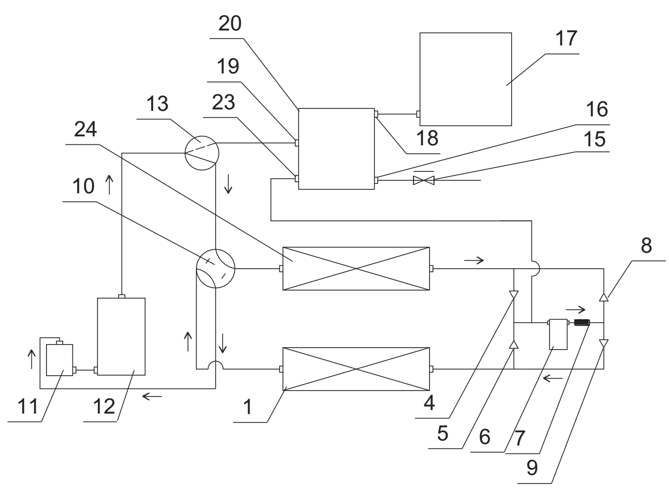

Fig. 17. Diagram of a three-heat-exchanger system of type C1 in which a domestic water heat exchanger was connected with a three-way valve and a receiver was employed: (1) indoor heat exchanger; (4, 5, 8, 9) check valves; (6) receiver; (7) expansion valve; (10) four-way valve; (11) gas–liquid separator; (12) compressor; (13) three-way valve; (15) solenoid water valves; (16) water inlet; (17) domestic water tank; (18) water export; (20) domestic Water heat exchanger; (24) outdoor heat exchanger [58].

This system and the other early similar systems [54–56] all employed the refrigerant rectification module but without the receiver, and some of type C1 systems [54,56] employed a three-way valve in place of the two-way valve for connecting the domestic water heat exchanger. The similar system was also applied for the ground source heat pump [57].

In 2007, Liu [58] proposed an improved three-heat-exchanger system of type C1 with a three-way valve for connecting the domestic water heat exchanger and a refrigerant rectification module consisted of a receiver, an expansion valve and four check valves (Fig. 17). The system also provided the same four operational modes as the system in Ref. [53] but better refrigerant managements in different operational modes.

A similar refrigerant rectification module was also employed in the similar system of Ref. [59], but two two-way valves were used in place of the three-way valve.

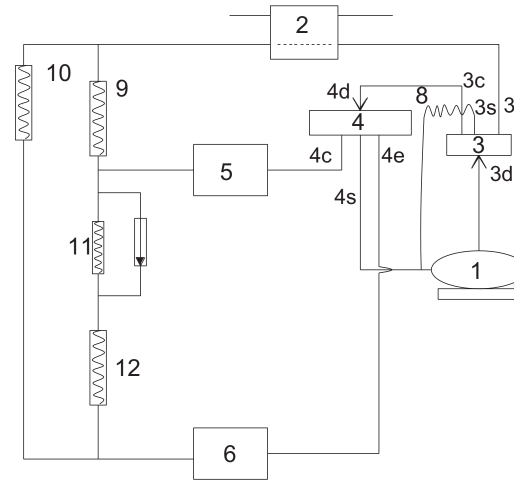

Fig. 18. Flow chart of a three-heat-exchanger system of type C2 in which a domestic water heat exchanger was connected with a four-way valve and no receiver was employed: (1) compressor; (2) domestic water heat exchanger; (3) second four-way valve; (4) original four-way valve; (5) outdoor heat exchanger; (6) indoor heat exchanger; (8) capillary; (9–12) expansion valves [60].

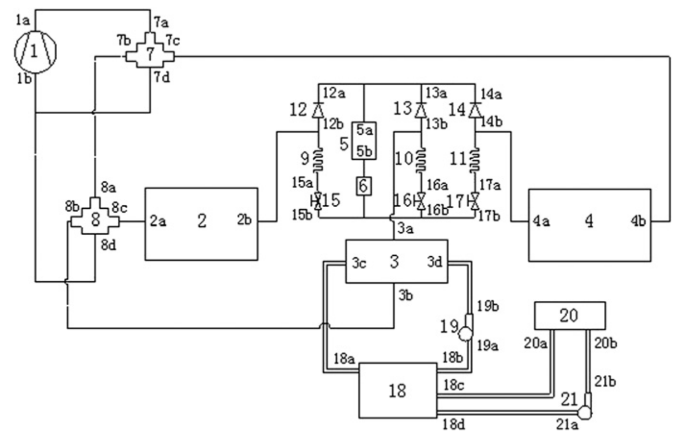

Fig. 19. Cycle layout of a three-heat-exchanger system of type C2 in which a domestic water heat exchanger was connected with a four-way valve and a receiver was employed: (1) compressor; (2) indoor heat exchanger; (3) domestic water heat exchanger; (4) outdoor heat exchanger; (5) receiver; (6) filter–dryer; (7) original four-way valve; (8) second four-way valve; (9–11) expansion devoices; (15–17) solenoid valves; (18) domestic water tank; (19, 21) water pumps; (20) auxiliary water heat exchanger [63].

3.3.2. *Connection with a four-way valve (C2)*

In 2003, Chen [60] introduced a three-heat-exchanger system of type C2 with a domestic water heat exchanger connected in parallel with the original four-way valve, in which a four-way valve replaced the two-way valve or three-way valve in the system of type C1 for connecting the domestic water heat exchanger (Fig. 18).

The advantage of employing the second four-way valve was that one end of the domestic water heat exchanger can be connected to the suction line of the compressor. Hence, the domestic water heat exchanger can function as an evaporator as well as a condenser, which can add two important energy saving modes: the hot water defrosting mode and solar assisted space heating mode if a solar collecting loop was integrated into the type C2 system.

The similar systems [61,62] provided the same operational modes as the system in Ref. [60], and employed the similar refrigerant rectification module without the receiver.

In 2010, Wang et al. [63] presented a three-heat-exchanger system of type C2 with a refrigerant rectification module consisted

of a receiver, a filter–dryer, three expansion valves, three solenoid valves and three check valves, in which the outdoor heat exchanger was connected in parallel with the original four-way valve and different heat sources can be used as the supplementary heat source (Fig. 19). Therefore, compared with the system in Ref. [60], the system provided not only additional two operational modes: solar assisted space heating and solar water heating, but also better refrigerant management.

The systems in Ref. [64,65] employed the similar refrigerant rectification modules with a receiver, but employed one expansion valve and two expansion valves respectively.

From the above discussions on Refs. [53–65], it can be found that the type C2 system is better than the type C1 system from the view of supplementary heat energy exploitation, because each pair of the three heat exchangers can be coupled as a condenser and an evaporator or vice versa in the type C2 system due to the employment of the second four-way valve.

3.4. Summary

The type C1 system is similar to the type A system because the domestic water heat exchanger in these systems always operates in high pressure, hence it cannot function as an evaporator, and then the system lacks two operational modes compared with the type C2 system. On the other hand, the operational modes of the type C2 system are similar to those of the type B2 system because the three heat exchangers are all connected in parallel. Morever, the type C2 system is better than the type B2 system from the view of the reliable and effective operations, because a cheap and reliable four-way valve in the type C2 system replaces the expansive reversible two-way or three-way direct action solenoid valves in the type B2 system, which is beneficial to the application of three-heat-exchanger systems.

From the evolution of the three-heat-exchanger systems of type A, type B and type C, it can be found that the configurations as well as operational modes of three-heat-exchanger systems mainly depend on the location of the domestic water heat exchanger in the refrigerant loop. The integrations of the receiver, expansion devices, solenoid valves and check valves are also necessary for the reliable and effective operation of these multi-functional systems, which are the key and difficult points in the design. Though the refrigerant loops become complicated in these systems compared with two-heat-exchanger systems, the second refrigerant loops are simplified greatly to operate the various modes. Therefore, three-heat-exchanger systems are especially suitable for the middle-size or small-size air source heat pump applications.

4. Multi-heat-exchanger systems

Though three-heat-exchanger systems have embodied energy saving operational modes to fulfill the three necessary functions, it was still needed to add some additional heat exchangers in the refrigerant loop to further improve the performance of the multi-functional heat pumps. According to the functions of additional heat exchangers, multi-heat-exchanger systems can be further divided into the following four types: (A) high temperature water systems; (B) thermal storage systems; (C) supplementary heat source systems; (D) recuperating systems.

4.1. High temperature water systems

In 2007, Chen [66] designed a four-heat-exchanger system with an additional domestic water heat exchanger connected in parallel with the refrigerant lines between the compressor and four-way valve based on a three-heat-exchanger system of type B1, in which the two domestic water tanks were connected in the water loop (Fig. 20).

The system provided not only the middle temperature water below 50 °C from the original domestic water tank with the latent heat released from the exhaust gas of the compressor in the heat pump water heating or space cooling/heat pump water heating modes, but also the high temperature water above 50 °C from the additional water tank with the high temperature sensible heat released from the exhaust gas in different operational modes.

Tong [67] also described a four-heat-exchanger system with an additional domestic water heat exchanger connected in similar way but based on a three-heat-exchanger system of type C1, in which the high temperature water was used for dehumidification and reheat of the room air.

Besides the original one, an additional domestic water heat exchanger was necessary for the type B or type C system to obtain the high temperature domestic water with the high temperature sensible heat from exhaust gas. Otherwise, the water temperature will not be so high if only the original domestic water heat exchanger is used because the temperature of the latent heat released from the exhaust gas is lower than that of the sensible heat.

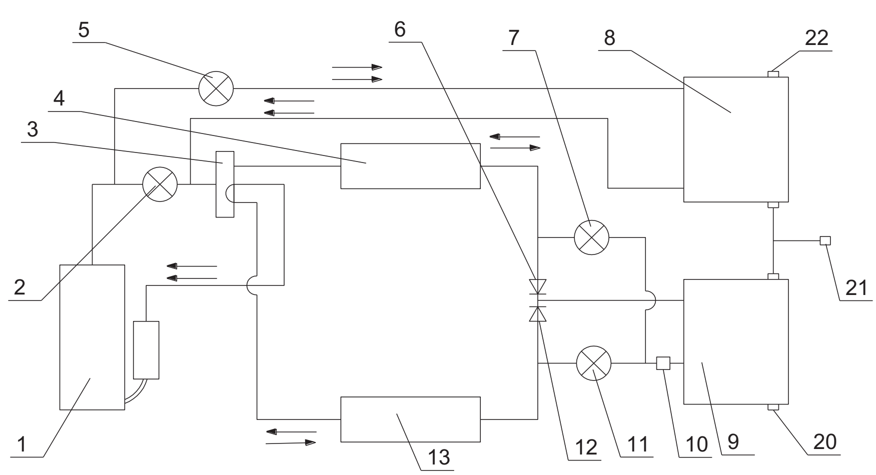

Fig. 20. Schematic view of a four-heat-exchanger system with an high temperature domestic water tank heat exchanger based on a three-heat-exchanger system of type B: (11) compressor; (2, 5, 7, 11) solenoid valves; (3) four-way valves; (4) outdoor heat exchanger; (6, 12) check valves; (8) high temperature water tank; (9) middle temperature water tank; (10) expansion valves; (13) indoor heat exchanger; (20) water inlet; (21, 22) water outlet [66].

4.2. Thermal storage systems

In 2010, Yang et al. [68] introduced a four-heat-exchanger system with an additional thermal storage water heat exchanger connected in parallel with the outdoor heat exchanger after the four-way valve based on a three-heat-exchanger system of type B2, in which phase-change materials were used in the thermal storage tank for increasing the solar heat storage density (Fig. 21).

The system not only provided all of the nine operational modes included in the above two-heat-exchanger systems and three-heat-exchanger systems, but also can fully take the advantage of solar heat by employing the phase-change materials in the additional domestic water heat exchanger.

Refs. [69,70] were two similar four-heat-exchanger systems based on a three-heat-exchanger system of type B1 and type A1, respectively. The additional thermal storage tank with phase-change materials can be used for heat storage and cold storage with the off-peak electricity to save the operating cost in winter and summer time, respectively.

However, the adoption of phase-change materials in the multifunctional heat pump will affect the stability of the cycle operation. Properties of phase-change materials, such as corrosion, environmental characteristic, are much related to the economy of multifunctional heat pumps. Therefore, the feasibility of phase-change materials should be studied in applications.

4.3. Supplementary heat source systems

In 2003, Wang et al. [71] presented a four-heat-exchanger system of DX-SAHP with an additional collector/evaporator connected in parallel with the outdoor heat exchanger based on a three-heat-exchanger system of type A2, in which a refrigerant rectification module consisted of a receiver, a expansion valve, a filter–dryer and four check valves was employed (Fig. 22).

The additional collector/evaporator was a key component for DX-SAHP, therefore, four heat exchangers were necessary for this system to provide the following six operational modes: common space cooling, common space heating, heat pump water heating, space cooling/heat pump water heating, solar assisted water heating and solar assisted space heating.

A similar four-heat-exchanger system based on a three-heat-exchanger system of type A1 was proposed in Ref. [72], in which

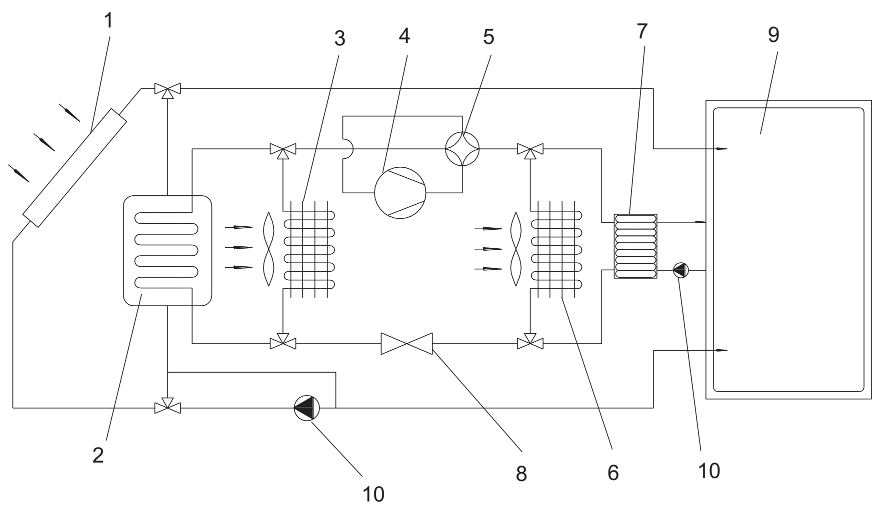

Fig. 21. Sketch of a four-heat-exchanger system with an additional hot water heat exchanger using phase-change materials based on a three-heat-exchanger system of type B2: (1) solar collector; (2) thermal storage tank; (3) outdoor heat exchanger; (4) compressor; (5) four-way valve; (6) indoor heat exchanger; (7) domestic water heat exchanger; (8) expansion valve; (9) domestic water tank; (10) water pump [68].

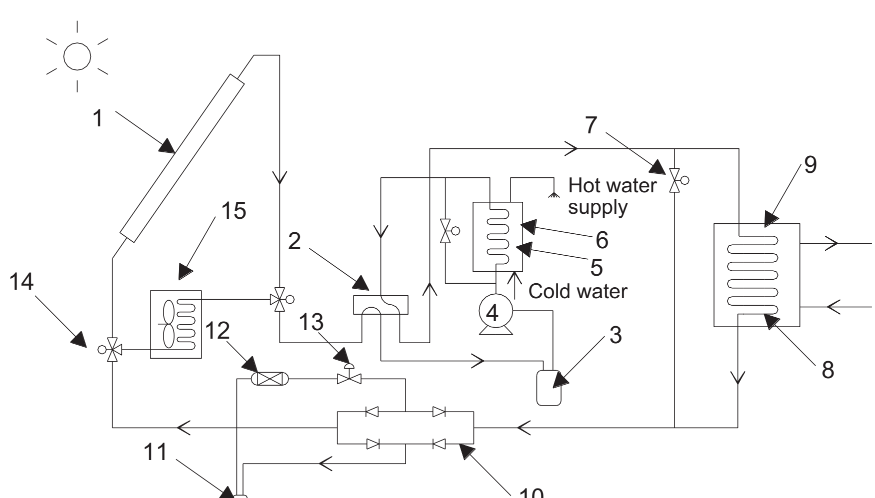

Fig. 22. Schematic diagram of a four-heat-exchanger DX-SAHP system with an additional collector/evaporator based on a three-heat-exchanger system of type A2: (1) collector/evaporator; (2) four-way valve; (3) gas–liquid separator; (4) compressor; (5) domestic water heat exchanger; (6) domestic water tank; (7) solenoid valve; (8) indoor heat exchanger; (9) thermal storage tank; (10) check valve; (11) receiver; (12) filter–dryer; (13) expansion valve; (14) three-way valve; (15) outdoor heat exchanger [71].

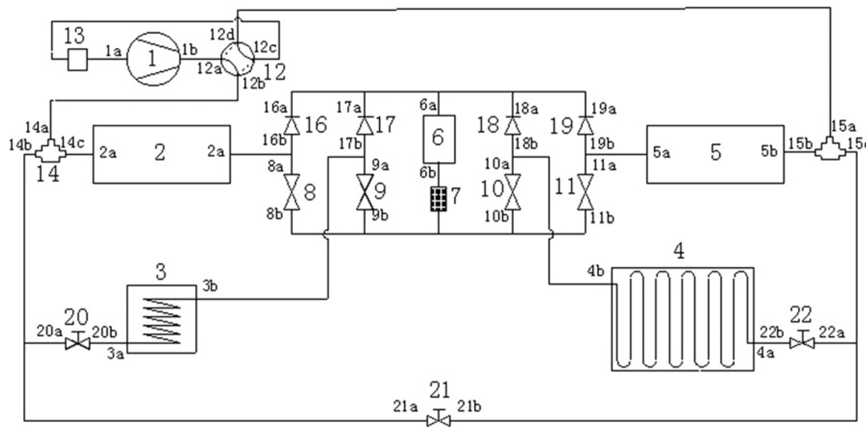

Fig. 23. Flow chart of a four-heat-exchanger DX-SAHP system with an additional collector/evaporator based on a three-heat-exchanger system of type B2: (1) compressor; (2) indoor heat exchanger; (3) domestic water tank; (4) collector\evaporator; (5) outdoor heat exchanger; (6) receiver; (7) filter–dryer; (8–11) expansion valves; (12) four-way valve; (13) gas–liquid separator; (14, 15) three-way valves; (16–19) check valves; (20–22) solenoid valves [73].

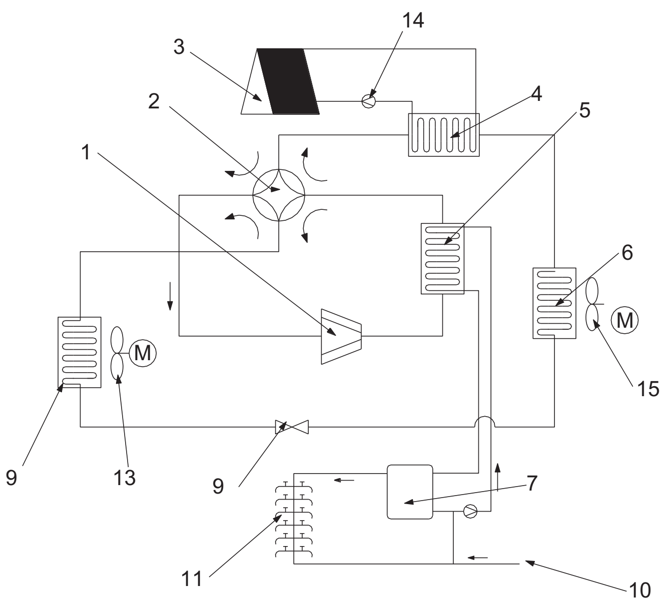

Fig. 24. Schematic drawing of a four-heat-exchanger IX-SAHP system with an additional domestic water heat exchanger based on a three-heat-exchanger system of type A1: (1) compressor; (2) four-way valve; (3) solar collector; (4) collector fluid heat exchanger; (5) domestic water heat exchanger; (6) outdoor heat exchanger; (7) domestic water tank; (8) expansion valve; (9) indoor heat exchanger; (10) water pump; (11) auxiliary water heat exchanger; (12) water inlet; (13) fan; (14) collector fluid pump [74].

the additional collector/evaporator connected in parallel with the indoor heat exchanger, and then it results in the absence of the solar assisted space heating operational mode compared with the system in Ref. [71]. But the system can obtain both heat and electricity from the solar energy due to the photovoltaic cell component integrated in the collector/evaporator.

In 2009, Wang et al. [73] introduced a four-heat-exchanger system of DX-SAHP with an additional collector/evaporator connected in parallel with the indoor and outdoor heat exchangers based on a three-heat-exchanger system of type B2, in which a refrigerant rectification module consisted of a receiver, a filter–dryer, four expansion valves and four check valves was employed (Fig. 23). Compared with the system in Ref. [71], it provided not only better refrigerant management but also two more operational modes: hot water defrosting and solar water heating.

In 2001, Liang et al. [74] proposed a four-heat-exchanger system of IX-SAHP with an additional solar collector fluid heat exchanger integrated in serial between the four-way valve and outdoor heat exchanger based on a three-heat-exchanger system of type A1, in which no refrigerant rectification module was employed (Fig. 24). From the discussions in Section 3, it has been known that the domestic water heat exchanger in the three-heat-exchanger system of type A1 can only function as the condenser but the evaporator. Therefore, an additional collector fluid heat exchanger is necessary for this system to provide the same six modes as the system in Ref. [73].

A similar four-heat-exchanger system based on a three-heat-exchanger system of type B2 has been proposed in Ref. [75], in which the additional collector fluid heat exchanger connected in parallel with the outdoor heat exchanger. The system provided the same modes as the system in Ref. [74], however, both of the systems cannot regulate the refrigerant mass and flow rate smoothly due to the absence of the refrigerant rectification module.

In 2011, Wang et al. [76] described a four-heat-exchanger system of IX-SAHP with an additional collector fluid heat exchanger connected in parallel with the indoor and outdoor heat exchangers based on a three-heat-exchanger system of type C2, in which a refrigerant rectification module consisted of a receiver, a filter–dryer, three expansion valves, three solenoid valves and four check valves was employed (Fig. 25).

From the discussions in Section 3, it has been known that the domestic water heat exchanger in the three-heat-exchanger system of type C2 can function as a condenser for the domestic heat pump water heating and also can function as evaporators for the solar assisted space heating. But in winter time, the water temperature will not be high enough for domestic usage if the system operates in the solar assisted space heating mode, and especially in severe winter conditions the water may be frozen.

Therefore, the system employed an additional domestic water heat exchanger only functioned as a condenser for the heat pump water heating while the original collector fluid heat exchanger only functioned as an evaporator for the solar assisted space heating. It is a good method to solve this conflict for the multi-functional heat pump system to utilize the supplementary heat source, though the initial cost of the system will increase. The system can provided not only the same operational modes in the system of Ref. [74] but also the proper refrigerant management by the refrigerant rectification module.

4.4. Recuperating systems

In 2010, Jiang et al. [77] introduced a five-heat-exchanger system with a recuperator integrated into the refrigerant loop of

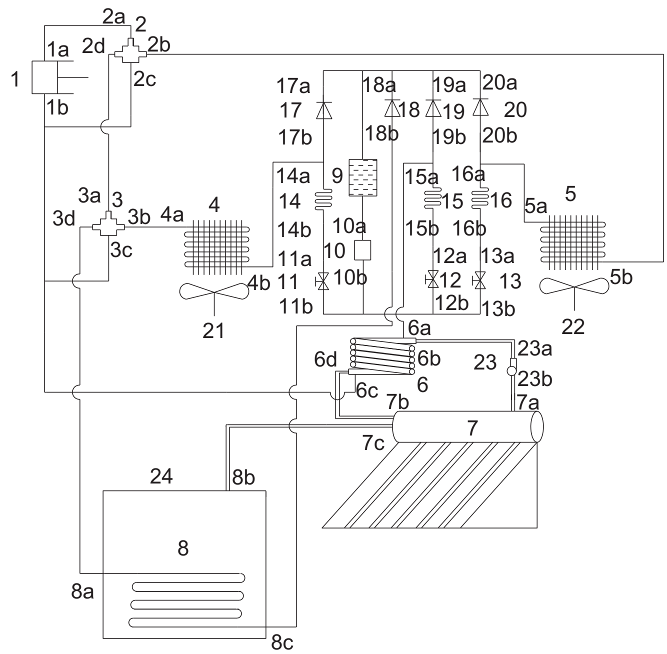

Fig. 25. Sketch of a four-heat-exchanger IX-SAHP system with an additional domestic water tank heat exchanger based on a three-heat-exchanger system of type C2: (1) compressor; (2,3) four-way valve; (4) indoor heat exchanger; (5) outdoor heat exchanger; (6) collector fluid heat exchanger; (7) collector fluid tank; (8) domestic water heat exchanger; (9) receiver; (10) filter–dryer; (11–13) solenoid valves; (14–16) expansion valves; (17–20, 25) check valves; (21, 22) fans; (23) collector fluid pump; (24) domestic water tank [84].

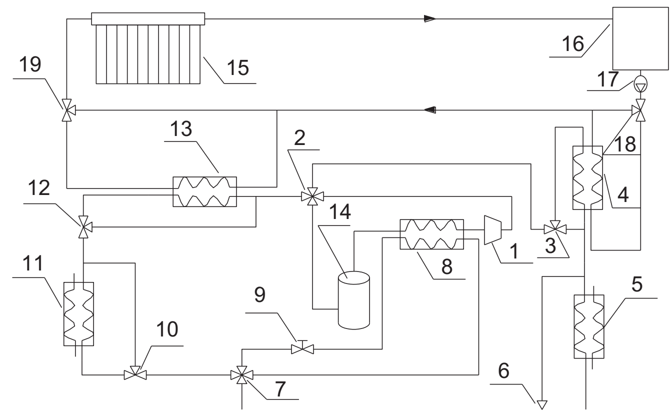

Fig. 26. Cycle layout of a five-heat-exchanger system with a recuperator integrated into the refrigerant loop of the CO_2 system based on a three-heat-exchanger system of type B2: (1) compressor; (2, 7) four-way valves; (3, 6, 10, 12, 18, 19) three-way valves; (4) domestic water heat exchanger; (5) indoor heat exchanger; (8) recuperator; (9) expansion valve; (11) outdoor heat exchanger; (13) collector water heat exchanger; (14) receiver; (15) solar collector; (16) domestic water tank; (17) water pump [77].

the CO_2 system based on a three-heat-exchanger system of type B2, in which an additional collector water heat exchanger for solar collecting was also connected in serial between the outdoor heat exchanger and original four-way valve (Fig. 26).

The recuperator was a key component in the transcritical CO_2 system for heat exchanging between the high and low pressure CO_2 to improve the thermal performance of the heat pump.

A second four-way valve was employed for the connection of the recuperator and other four heat exchangers to ensure the refrigerant going through the recuperator ahead of the expansion valve, because each of the other four heat exchangers may function as a condenser or an evaporator in different operational modes. A bypass line was employed for each of the heat exchangers in the system except the recuperator. The system provided all the operational modes as the system in Ref. [68] except the solar space heating mode.

A similar four-heat-exchanger CO_2 systems based on a three-heat-exchanger system of type B2 has been proposed in Ref. [78], in which a third four-way valve was employed and thus the two water heat exchangers in the system of Ref. [77] can be combined into one unit.

4.5. Summary

It can be found that the above multi-heat-exchanger systems were developed from the three-heat-exchanger systems by the integration of the high temperature water heat exchanger, or thermal storage heat exchanger, or collector fluid heat exchanger, or recuperator for further improving the heat pump performance. Though the configuration of the system becomes more complicated, it indicates a trend of the development of multifunctional heat pumps.

5. Conclusions

The research on vapor compression heat pumps in China began in 1950s, but it is not until 1990s that the pace quickened up. At the end of 2000, the heat pump air conditioner became widespread as well as the water source heat pump air conditioning systems. With growing concerns about worldwide energy and environmental sustainability, heat pump water heaters and solar water heaters became popular in China after 2000. The combinations between the heat pump air conditioner, heat pump water heater and solar water heater promote the rapid development of multifunctional heat pumps.

The heat pump air conditioner was the fundamental component of a multifunctional heat pump. Versatile configurations of multifunctional heat pumps were evolved from the integration of the domestic water heat exchanger with the refrigerant loop of the heat pump air conditioner by various approaches. According to the amount of heat exchangers in the refrigerant loop, the multifunctional heat pump is divided into three categories in this paper as follows: (1) two-heat-exchanger systems; (2) three-heat-exchanger systems; (3) multi-heat-exchanger systems.

The important operational modes included in the introduced multifunctional heat pumps can be summed up in Table 2, in which mode numbers are denoted as follows: (1) common space cooling; (2) common space heating; (3) heat pump water heating; (4) space cooling/heat pump water heating; (5) hot water defrosting; (6) solar assisted water heating; (7) solar assisted space heating; (8) solar water heating; (9) solar space heating. Other supplementary heat sources can also be used as the solar energy.

Mode (1) and Mode (2) are the two operational modes embodied in a heat pump air conditioner. Mode (3) is the operational mode of a heat pump water heater. Mode (8) and Mode (9) are the two operational modes included in a solar water heater. Mode (4)–Mode (7) are four energy saving operational modes generated from the combinations, which are the important features of the multifunctional heat pumps.

From the above discussions, following conclusions can be derived:

(1) Refrigerant loops of two-heat-exchanger systems are simple and reliable similar to those of heat pump air conditioners, but the compound heat exchanger or additional domestic water tank or the supplementary heat source should be employed, hence the second refrigerant loops become complicated to operate the various operational modes [22,24,26]. Therefore, two-heat-exchanger systems are more suitable for the large-size heat pump applications.

Table 2
Important operational modes of the introduced multifunctional heat pumps.

Systems		References	Operational modes								
			(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Two-heat-exchanger systems		[20]	√	√	×	√	×	×	√	√	×
		[22]	√	√	√	×	×	×	×	√	√
		[24]	√	√	√	√	×	√	√	√	×
		[26]	√	√	√	√	×	√	√	√	√
Three-heat-exchanger systems	A1	[27]	√	√	√	√	×	×	×	×	×
		[31]	√	√	√	√	×	×	×	×	×
	A2	[32]	√	√	√	√	×	×	×	×	×
		[36]	√	√	√	√	×	×	×	×	×
		[37]	√	√	√	√	×	√	√	√	×
	B1	[38]	√	√	×	√	√	×	√	√	×
		[40]	√	√	√	√	√	×	√	√	×
		[42]	√	√	√	√	√	×	×	×	×
	B2	[43]	√	√	√	×	√	×	×	×	×
		[44]	√	√	×	√	×	×	√	√	×
		[48]	√	√	√	√	√	×	√	√	×
	C1	[53]	√	√	√	√	×	×	×	×	×
		[58]	√	√	√	√	×	×	×	×	×
	C2	[60]	√	√	√	√	√	×	×	×	×
		[63]	√	√	√	√	×	×	√	√	×
Multi-heat-exchanger systems		[66]	√	√	√	√	×	×	×	×	×
		[68]	√	√	√	√	√	√	√	√	√
		[71]	√	√	√	√	×	√	√	×	×
		[73]	√	√	√	√	√	√	√	√	×
		[74]	√	√	√	√	√	√	√	√	×
		[76]	√	√	√	√	√	√	√	√	×
		[77]	√	√	√	√	√	√	√	√	×

(2) Integrations of the domestic water heat exchanger and refrigerant rectification module in the refrigerant loop of the heat pump air conditioners evolved the three-heat-exchanger systems of type A, type B and type C. Though refrigerant loops become complicated, the second refrigerant loops were simplified to operate the various operational modes. Therefore, three-heat-exchanger systems are more suitable for the small-size or middle-size air source heat pump applications.
(3) The systems of type A were the earliest proposed three-heat-exchanger heat pump systems, which are simple and practical in configuration, but their operational modes are limited because the domestic water heat exchangers cannot function as evaporators. Type A2 systems possess the potential superior thermal performance over type A1 systems.
(4) The systems of type B were proposed after the systems of type A and can provide more operational modes because the domestic water heat exchangers can function as condensers or evaporators. Type B1 systems are simple in configuration, but their applications are confined due to the difficult in the employment of the refrigerant receiver. Type B2 systems possess the potential superior operational reliability over type B1 systems, but their applications are also limited due to the employment of expensive direct action solenoid valves.
(5) The systems of type C were proposed after the systems of type B. The operational modes of type C1 systems are confined due to the same reason as type A systems. Type C2 systems provide the same operational modes as type B2 systems but with simpler configurations and more reliable performance as type C1 systems. From the view of the reliable and effective operations, type C2 systems are superior over type B2 systems.
(6) Multi-heat-exchanger systems were evolved from three-heat-exchanger systems by integrations of the functional heat exchangers in the refrigerant loops to improve the system performance, however, system configurations become complicated.

Late in the 1970s, multifunctional heat pumps appeared in several American patents [79], but it seems no research paper on the application of the multifunctional heat pump can be found. It was not until at the beginning of the 21st century, more and more theoretical and experimental research results have been reported in the international journals [80–89], in which most of the studies were conducted by Chinese researchers.

Compared with the worldwide development of heat pump heating systems [5,6,90], solar water heaters [91,92] and solar air collectors [93,94], multifunctional heat pumps have not well developed yet. The configuration of a multifunctional heat pump is the key point for its application, because it fundamentally determines the initial cost, operating cost and operating reliability of the heat pump. It is reasonable to make a compromise between the simplicity of the configuration and the versatile operational modes in the design of the multifunctional heat pump under different application conditions. However, the promising characteristics of energy saving and high utilization ratio will stimulate the developments and applications of multifunctional heat pumps in China as prosperous as heat pump water heaters or solar water heaters.

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References

[1] Thomson W. On the economy of the heating or cooling of buildings by means of air. Glasgow Philosophical Society Proceedings 1852:269–72.
[2] IEA Heat Pump Centre. Peter Ritter von Rittinger International Heat Pump Award. Available from: 〈http://www.heatpumpcentre.org/en/hppactivities/rittingeraward/Sidor/default.aspx〉.
[3] Zoelly H. Heizverfahren. Patent CH59350; 1912.
[4] The Heat Pump. Available from: 〈http://what-when-how.com/inventions/heatpumpinventions/〉 [accessed 29.06.11].

[5] Hepbasli A, Kalinci Y. A review of heat pump water heating systems. Renewable and Sustainable Energy Reviews 2009;13:1211–29.
[6] Ozgener O, Hepbasli A. A review on the energy and exergy analysis of solar assisted heat pump systems. Renewable and Sustainable Energy Reviews 2007;11:482–96.
[7] Kara O, Ulgen K, Hepbasli A. Exergetic assessment of direct-expansion solar-assisted heat pump systems: review and modeling. Renewable and Sustainable Energy Reviews 2008;12:1383–401.
[8] Wilson LT. Method and system for utilizing solar energy. Patent US 2575478; 1951.
[9] Spore P, Ambrose ER. The heat pump and solar energy. In: Proceedings of the world symposium on applied solar energy held in Phoenix, Arizona; 1955.
[10] Morgan RG. Solar assisted heat pump. Solar Energy 1982;21(2):129–35.
[11] Ma ZL,Yang ZQ, Ma GY. Review and prospect of development of the heat pump in China. In: Proceedings of the national HVAC annual conference held in Nanning, China; 2000. p. 470–3.
[12] Deng YL, Yan M. Device for air-conditioning and hot water supply. Patent CN 85202970; 1986.
[13] Zheng ZY. Combined air source and water source heat pump using screw compressor. Patent CN86105016; 1988.
[14] Shi X. A water source heat pump utilizing the soil for heat storage. Patent CN91111356.8; 1993.
[15] Xiao RZ. Ground source heat pump for air-conditioning and hot water supply. Patent CN92101230.6; 1993.
[16] Zhao J, Ma YT, Zheng ZH, Fang CC. Experimental study of solar assisted heat pump system for water heating. Acta Energiae Solaris Sinica 1993;14(4): 306–10 (in Chinese).
[17] Bi YH. Performance study on a solar-ground source heat pump for winter heating, ms in refrigeration engineering. Tianjin, China: Tianjin University; 1995 (in Chinese).
[18] Xu BA. Air-conditioner and water heater. Patent CN97233681.8; 1999.
[19] Kuang YH, Wang RZ, Yu LQ. Experimental study of solar assisted heat pump (SAHP) system for heat supply. Acta Energiae Solaris Sinica 2002;23(4): 408–13 (in Chinese).
[20] Zhou GH, Liu Y, Dong XJ. Air-solar compound heat pump device. Patent CN 200720091298.7; 2008.
[21] Zhou GH, Dong XJ, Liu Y. Solar-ground source compound heat pump device. Patent CN200820069362.6; 2008.
[22] Sun ZY, Zhou Z, Xiao JJ, Li W, Zhao W. Solar-water combined source heat pump for HVAC. Patent CN200520031937.1; 2007.
[23] Yuan MH. Unit for cooling, heating and hot water supply combined with solar energy. Patent CN200920122428.8; 2010.
[24] Luo WL. A multifunctional energy-saving air-conditioning unit. Patent CN 200720062226.X; 2008.
[25] Chen GM, Gong XM, Wang Q, Cai YN, Zhang SB. Self-balanced solar-geothermal heat pump system. Patent application CN200920192468.X; 2009.
[26] He DH, Ke LB. Solar-assisted air cooled air-conditioner with three functions. Patent application CN200920264723.7; 2009.
[27] Peng JH. Heat pump for air-conditioning and hot water supply. Patent CN 200510031695.0; 2006.
[28] Cao YF, Xie ZY, Xie HR. Heat pump air-conditioner and water heater. Patent CN200320132218.X; 2005.
[29] Fang XD, Li XJ, Zhao HY, Yang TT. Direct-expansion ground source heat pump water heater. Patent CN200710022835.7; 2007.
[30] Zhu JY. A safe and effective heat pump air-conditioner and water heater. Patent application CN200910040172.0; 2009.
[31] Mou D. Multifunctional heat pump system. Patent CN200820096650.0; 2009.
[32] Li HD. Device for air-conditioning and hot water supply. Patent CN200620-023243.8; 2007.
[33] Xu BA. Split-type air-conditioner and water heater. Patent CN98222949.6; 1999.
[34] Gao JM. Split-type combination air source air-conditioner and water heater. Patent CN200820211146.0; 2009.
[35] Jiang HM, Wang Y, Ma ZL, Yao Y. Experimental research on the dynamic characteristics of the energy-saving type air conditioner with domestic hot water supply. Heating Ventilating and Air Conditoning 2005;35(9):125–30 (in Chinese).
[36] Ye YX. Air-conditioner with hot water supply. Patent application CN200920183197.1; 2009.
[37] Wang Q, Xu YJ, Chen GM, Liang GF, Chen X. A frost-free solar-assisted multifunctional heat pump system. Patent CN200910099402.0; 2009.
[38] Ding GL. Combined energy source air-conditioner and water heater. Patent CN200610027968.9; 2006.
[39] Wang KM. A split-type multifunctional heat pump air-conditioner. Patent CN98234559.3; 1999.
[40] Wang Q, Li JR, Chen GM, Xu JY. Solar assisted multifunctional heat pump system. Patent CN200610050285.5; 2006.
[41] Wang Y. Air-conditioner with heat pump water heater. Patent CN002290-50.2; 2001.
[42] Zhu JW, Su YG. Multifunctional heat pump unit. Patent CN200820044832.3; 2009.
[43] Huang XF. Split-type heat pump air-conditioner and water heater. Patent CN200410015396.3; 2005.
[44] Chen WX. Mode studies on dual-source solar heat pump, ms in HVAC engineering. Nanjing, China: Nanjing University of Science; 2004 (in Chinese).
[45] Dong YP, You SJ. Economic analysis on solar-ground source heat pump comprehensive system. Gas and Heat 2003;23(12):734–40 (in Chinese).
[46] Sun L. Optimization research on dual-source solar assisted heat pump and hot water system, ms in HVAC engineering. Nanjing, China: Nanjing University of Science; 2010 (in Chinese).
[47] Wu QR, Wang SG. Multifunctional solar-air source heat pump and adaptive analysis in cold regions. Solar Energy 2010;10:36–9 (in Chinese).
[48] Wang Q, Liang GF, Chen GM, Li JR, Xu YJ, Chen X. An indirect-expansion multifunctional solar-assisted air-conditioning system. Patent CN 200910099400.1; 2009.
[49] Wang Q, Li JR, Chen GM. Multifunctional solar-assisted integrated air-conditioning heater. Patent CN200710070046.0; 2008.
[50] Wang Q, Liang GF, Chen GM, Li JR. A multifunctional solar-assisted air-conditioning system. Patent CN200810120282.3;2009.
[51] Li SH, Zhang XS, Du K, Cai L. Multifunctional heat pump air-conditioner and water heater. Patent CN03131988.2; 2003.
[52] Huang X. An air-conditioner and water heater. Patent CN200520075538.5; 2006.
[53] Liu SM. Air-conditioner and water heater. Patent CN200520136009.1; 2007.
[54] Wu ZL. Air-conditioner and water heater. Patent CN00126581.4; 2002.
[55] Chen ZS. An energy-saving heat pump air-conditioner and water heater for four seasons. Patent CN00264455.X; 2002.
[56] Chen ZS. An energy-saving heat pump air-conditioner and water heater for four seasons. Patent CN02116049.X; 2002.
[57] Li SH, Zhang XS, Du K, Cai L. A multifunctional ground source heat pump water heater. Patent CN200910024490.8; 2009.
[58] Liu SM. Air-conditioner and water heater. Patent CN200720087891.4; 2008.
[59] Ruan WL. Air-conditioner and water heater. Patent CN201020239829.4; 2011.
[60] Chen ZQ. A multifunctional heat pump air-conditioner and water heater system. Patent CN03278456.2; 2004.
[61] Dong YG. Multifunctional air-conditioner and water heater. Patent CN200320130969.8; 2004.
[62] Wang S. An air source air-conditioner and water heater. Patent CN200420052947.9; 2005.
[63] Wang Q., Liang GF, Chen GM, Li JR. A multi-heat-source assisted multi-functional heat pump. Patent application CN201010114627.1; 2010.
[64] Gu WP, Li GQ. Heat pump air-conditioner and water heater unit. Patent CN200810021278.1; 2008.
[65] Shi M, Zhang XP, Zhong Y, Zhong YZ, Yue HB, Chen LQ, et al. Easy defrost multifunctional heat pump water heater. Patent CN200820215; 2009.
[66] Chen JC. Energy-saving air conditioner water heater. Patent CN 200710031998.1; 2009.
[67] Tong FX. A heat pump air-conditioner and water heater. Patent application CN201010149776.1; 2010.
[68] Yang L, Zhang XS. Air source heat pump assisted solar water heater using phase change materials for thermal storage. Patent application CN201010277418.9; 2010.
[69] Ying WJ. Multifunctional air-conditioning and heating unit. Patent CN9922-8716.2; 2000.
[70] Fang GY, Zhang M, Yang F, Li H. Small-size multifunctional solar-assisted air conditioner with thermal storage. Patent CN200710019255.2; 2007.
[71] Wang RZ, Kuang YH, Xu YX, Wu JY. Direct-expansion solar air-conditioner and hot water supply system. Patent CN03150625.9; 2004.
[72] Fang GY, Zhang M, Yang F, Wu SM, Li H. Integrated solar-assisted heat pump system. Patent CN200810018983.6; 2008.
[73] Wang Q, Liang GF, Chen GM, Chen X, Xu YJ. A direct-expansion multi-functional solar assisted heat pump system. Patent CN200910099401.6; 2009.
[74] Liang TY. Multifunctional air-conditioning and water heating device. Patent CN01242961.9; 2002.
[75] Yang JC, Ji J, Pei G, Jang AG, He W. Experimental investigation of an indirect expansion solar assisted multifunctional domestic heat pump. Journal of University of Science and Technology of China 2007;37(1):53–60 (in Chinese).
[76] Wang Q, Liu YQ, Chen GM, Liang GF, He W, Li JR. An indirect-expansion solar-assisted heat pump system. Patent application CN201110079756.6; 2011.
[77] Jiang PX, Sun ZH, Wang GL. Solar-assisted air source transcritical carbon dioxide heat pump air conditioning system. Patent CN200710062610.4; 2007.
[78] Xie YB, Liu JL, Lun LY, Liu CT. A transcritical carbon dioxide heat pump air conditioner and water heater employing the condensing heat. Patent application CN201010521709.8; 2010.
[79] Wsllin M, Shantzer A. Heat pumps with solar heat source. Patent US 4030312; 1977.
[80] Kuang YH, Wang RZ, Yu LQ. Experimental study on solar assisted heat pump system for heat supply. Energy Conversion and Management 2003;44: 1089–98.
[81] Ji J, Pei G, Chow TT, He W, Zhang AF, Dong J, et al. Performance of multi-functional domestic heat-pump system. Applied Energy 2005;80:307–26.
[82] Trillat-Berdal V, Souyri B, Fraisse G. Experimental study of a ground-coupled heat pump combined with thermal solar collectors. Energy and Buildings 2006;38:1477–84.
[83] Hawlader MNA, Rahman SMA, Jahangeer KA. Performance of evaporator-collector and air collector in solar assisted heat pump dryer. Energy Conversion and Management 2008;49:1612–9.
[84] Stojanovic B, Akander J. Build-up and long-term performance test of a full-scale solar-assisted heat pump system for residential heating in Nordic climatic conditions. Applied Thermal Engineering 2010;30:188–95.

[85] Gong GC, Zeng W, Wang LP, Wu C. A new heat recovery technique for air-conditioning/heat-pump system. Applied Thermal Engineering 2008;28:2360–70.
[86] Li H, Yang HX. Energy and exergy analysis of multi-functional solar-assisted heat pump system. International Journal of Low-Carbon Technologies 2010;5:130–6.
[87] Wang Q, Liu YQ, Liang GF, Li JR, Sun SF, Chen GM. Development and experimental validation of a novel indirect-expansion solar-assisted multi-functional heat pump. Energy and Buildings 2011;43:300–4.
[88] Ge FH, Guo XL, Hu ZC, Chu Y. Energy savings potential of a desiccant assisted hybrid air source heat pump system for residential building in hot summer and cold winter zone in China. Energy and Buildings 2011;43:3521–7.
[89] Lazzarin RM. Dual source heat pump systems: operation and performance. Renewable and Sustainable Energy Reviews 2012;52:77–85.
[90] Kara O, Ulgen K, Hepbasli A. Exergetic assessment of direct-expansion solar-assisted heat pump systems: review and modeling. Renewable and Sustainable Energy Reviews 2008;12:1383–401.
[91] Jaisankar S, Ananth J, Thulasi S, Jayasuthakar ST, Sheeba KN. A comprehensive review on solar water heaters. Renewable and Sustainable Energy Reviews 2011;15:3045–50.
[92] Hossain MS, Saidur R, Fayaz H, Rahim NA, Islam MR, Ahamed JU, et al. Review on solar water heater collector and thermal energy performance of circulating pipe. Renewable and Sustainable Energy Reviews 2011;15:3801–12.
[93] Alkilani MM, Sopian K, Alghoul MA, Sohif M, Ruslan MH. Review of solar air collectors with thermal storage units. Renewable and Sustainable Energy Reviews 2011;15:1476–90.
[94] Chamoli S, Chauhan R, Thakur NS, Saini JS. A review of the performance of double pass solar air heater. Renewable and Sustainable Energy Reviews 2012;16:481–92.